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Feeding the herds: Stable isotope analysis of animal diet and its implication for understanding social organisation in the Indus Civilisation, Northwest India

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ABSTRACT

The way that people manage their livestock tells us about their interactions with the landscape, particularly the nature of adaptation to specific environments, social organisation, resilience and long-term farming sustainability. Globally, there is considerable variation in how these practices are manifested, due to differences in water availability, levels of environmental diversity and aridity, and also the nature of cultural choices. South Asia's Indus Civilisation (*c.*3000–1500 BCE) provides an important opportunity for investigating how populations managed their animals, because the region shows considerable diversity in rainfall distribution, seasonality and intensity, which results in marked environmental variability that is susceptible to change over time. The latter is particularly significant when it comes to consideration of the impact of the 4.2 ka BP event and its relation to the deurbanisation of the Indus Civilisation.

This paper presents carbon isotope data from animal teeth from nine archaeological sites distributed across northwest India that are suitable for exploring how diverse practices were, and how animal management strategies changed through time. These data show clear differentiation in feeding practices between species, with cattle and water buffalo consuming very high proportions of C_4 plants, while sheep and goat ate varying quantities of C_3 and C_4 plants. This pattern is generally consistent across sites and throughout different periods, suggesting that the strategy was adapted to a range of environmental conditions and settlements of different sizes. We suggest that humans controlled cow and water buffalo diets, and they were likely provided with fodder. In contrast, sheep and goats had a less controlled diet, and were presumably more likely to roam the landscape. These animal management strategies must have involved some separation of tasks, although it remains unclear if this was on a household, settlement or population level.

1. Introduction

The study of animal management strategies has a long history within archaeology. It provides important insights into understanding how past peoples lived their lives, interacted with the landscape and organised themselves to ensure that their subsistence requirements were satisfied. The extent to which such practices were maintained through time and across space can also provide insight into how adaptable they were to different environmental and social circumstances, their resilience to adversity and their long-term sustainability. The Indus Civilisation (*c.*3000–1500 BCE) has traditionally been viewed as having uniform and integrated material culture and cultural practices (e.g. Marshall, 1931). However, more recent research indicates that while there are broad similarities in some aspects of material culture throughout the Indus zone, variation is also evident (e.g. Chase et al., 2014; Meadow and Kenoyer, 1997; Parikh and Petrie, 2019; Petrie et al., 2017, 2018; Roux and Courty, 1998). This pattern extends to arable agriculture, with aspects of Indus cuisine, such as the

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exploitation of bread wheat, being widespread, but differences are also seen in cropping strategies relating to the variability and seasonality of water availability (e.g. Petrie et al., 2017; Petrie and Bates, 2017; Vishnu-Mittre and Sacithri, 1982; Weber, 1999; Weber et al., 2010). There have been a number of important studies of animal exploitation at Indus sites (e.g. Joglekar et al., 2013; Meadow, 1996; Meadow and Patel, 2003; Sharada, 2018; Thomas, 2002), but there remains much to learn about Indus animal management strategies and whether or not these varied across the Indus Civilisation. Thus far, the use of stable isotope analysis has been limited (e.g. Chakraborty et al., 2018; Chase et al., 2014; Chase et al., 2020). Consideration of not only which animals were present but also how they were used and fed are essential for understanding the social processes related to animal management, and for considering the adaptation and sustainability of Indus pastoral agriculture and its resilience to climate change, particularly in relation to the 4.2 ka BP climate 'event' and the deurbanisation of the Indus Civilisation by *c.*1900 BCE.

This paper presents a large new carbon isotope dataset from animal teeth from ancient settlement sites in northwest India. We infer the diets of cattle, water buffalo, sheep, goat, pig and various wild animals and consider the implication that these data have for human daily lives and social organisation. Samples from a range of settlement sizes are considered, allowing us to document the variety in animal management strategies within northwest India as compared to published data from contemporary sites in Gujarat (Chakraborty et al., 2018; Chase et al., 2014; Chase et al., 2020), which lies to the south. These two regions are important as they represent the two areas that lie at the easternmost edge of the distribution of Indus Civilisation settlements (Fig. 1a). By taking a diachronic perspective, we also consider how animal management strategies may have varied through time, and what this tells us about the sustainability and resilience of Indus animal management practices. The paper poses three specific questions. Do we observe the same isotopic patterning in all species? Do domesticated animals show the same isotopic patterning as wild animals? Do we see a change over time, space and site size?

2. Background

2.1. The Indus Civilisation

The Indus Civilisation stretched over the Indus River basin and its surrounding areas, spanning an extensive area of northwest India and Pakistan. It is characterised as having a phase of urbanism, but as there are only four or five known cities compared to thousands of smaller settlements (Fig. 1a), and it is likely that most people did not live in cities (Fairservis, 1961; Parikh and Petrie, 2019; Sinopoli, 2015). Pastoralism was an important component of urban and rural subsistence, and although pastoralism may have been attached to sedentary communities, it is possible that there were mobile pastoral communities coexisting with sedentary populations within the Indus zone (e.g. Guha, 1994), indeed pastoral communities existed in surrounding areas in the Mediaeval period (Varma, 1991). Direct evidence for mobile populations in the form of campsites is limited to Gujarat and Cholistan (e.g. Mughal, 1997; Rissman and Chitalwala, 1990). However, such sites are generally ephemeral, and evidence potentially will not have survived, particularly given the complicated alluvial sediment profiles associated with the Indus River basin and the extensive agriculture over parts of the region today.

There are a number of different chronological schemes for dividing up the periods of the Indus Civilisation, but most dating systems implicitly or explicitly divide the broad span into 'pre-urban', 'urban' and 'post-urban' phases (Possehl, 1977). These phases are alternatively referred to as 'Early Harappan' (3200–2600 BCE), 'Mature Harappan' (2600–1900 BCE, also known as the 'Harappa phase'; Kenoyer, 1998) and 'Late Harappan' (1900–1600 BCE; e.g. Mughal, 1970; Possehl, 2002; Wright, 2010). At Harappa, the urban phase is divided into three sub-phases, Harappa 3a (2600–2450 BCE), 3b (2450–2200 BCE), and 3c (2200–1900 BCE) (Kenoyer, 1991, 2008). However, the leitfossils that differentiate these phases are not always attested in regional assemblages, and cross-correlations are only possible with the assistance of radiocarbon dates. Here, we separate our samples from the Mature Harappan (MHar) period into three phases, MHar i (2600–2450 BCE), MHar ii (2450–2200 BCE) and MHar iii (2200–1900 BCE), which correspond chronologically to Harappa 3a, 3b and 3c. We adopt this approach to maintain coherence with the Harappa chronology, but also to emphasise that these sites present a regionally distinct manifestation of Indus material culture.

Today, the Indus River basin is environmentally diverse, incorporating areas of arid hot desert, arid hot steppe, and warm and temperate areas with dry winters and hot summers (Wright, 2010; Petrie, 2013, 2017; Petrie et al., 2017). Different areas receive water in the form of summer and/or winter rainfall, snowmelt from the Himalayas, and surface and river runoff from these features (Petrie et al., 2017). Palaeoclimatic proxy records are not evenly distributed across the region, but they do suggest complex patterns of variation in rainfall intensity across the Holocene, with higher levels of rainfall in the early Holocene, progressive aridification in the mid Holocene, some evidence for increasing precipitation *c.*4.5 ka BP, and then evidence of weakening winter and summer rainfall from *c.*4.3–4.2kya BP (Dixit et al., 2014, 2018; Giesche et al., 2019; see Dixit and Tandon, 2016; Misra et al., 2019). Geographically, the Indus River basin and its surrounding areas include alluvial plain, piedmonts, mountains, desert and coastal areas, and Indus settlements are found in each of these contexts.

This variation in water supply and geography would have (and continues to) produced a range of distinct ecological niches that influenced Indus agricultural strategies. Indus Civilisation populations cultivated a range of winter (*rabi*) crops including wheat and barley, and summer (*kharif*) crops including native millets, rice and tropical pulses (Petrie and Bates, 2017; Weber, 1999, 2003; Wright, 2010). Variation in past cropping strategies is seen between the different regions, resulting from the differences in ecological setting and water availability. It has been suggested by several scholars (Petrie and Bates, 2017; Weber, 1999; Weber et al., 2010) that winter crops predominate in Sindh and Baluchistan (e.g. Tengberg, 1999) while summer crops predominate in Gujarat, which does not benefit from winter rainfall (e.g. Reddy, 2003; Weber, 1991, 1999). In Pakistani Punjab, both winter and summer crops are found though winter crops predominate (e.g. Weber, 1999), whereas in Haryana and Punjab in northwest India, a diverse mix of winter and summer crops is attested (e.g. Bates, 2016; Petrie et al., 2016; Petrie and Bates, 2017; Üstünkaya et al., 2020). Nevertheless, there are some sites that seem to challenge this pattern, for example Kanmer in Gujarat where barley is attested in the Early and Mature Harappan (Pokharia et al., 2011) and Sohr Damb in Baluchistan where a diverse range of crops are found, including summer crops (Beneke and Neef, 2005). Significantly, some aspects of Indus cuisine appear to have been widespread in spite of ecological variability; bread wheat, for example, was used throughout the Indus zone even in areas not well suited to growing winter crops (Madella, 2014).

2.2. Indus Zooarchaeology

Broad surveys of the use of animals at Indus Civilisation settlements have suggested a degree of uniformity and/or homogeneity in terms of the species found (Joglekar et al., 2013; Meadow, 1996; Meadow and Patel, 2003; Miller, 2004). Regardless of site size, Indus zooarchaeological assemblages are characterised by a high proportion of cattle and/or water buffalo remains, with a smaller proportion of sheep/goat, along with a small representation of pig, wild terrestrial animals and aquatic resources (e.g. Joglekar et al., 2013; Meadow and Patel, 2003; Miller, 2004). The broad similarities do, however, mask multiple layers of variation in patterns of animal exploitation within and between Indus settlements.

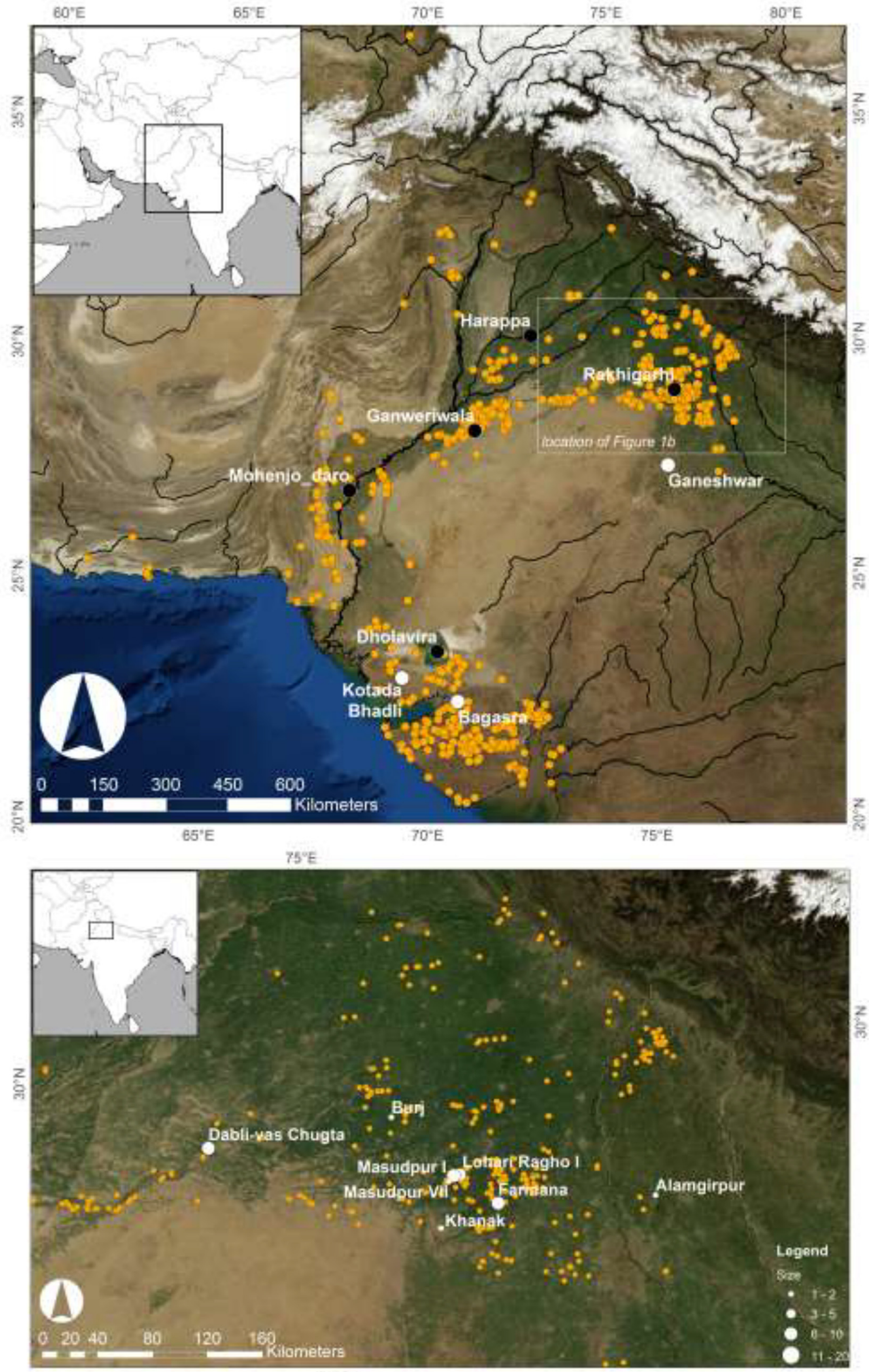

Fig. 1. Maps of sites mentioned in the text: a) Map of the Indus Civilization with known sites shown by orange circles, city sites by black circles and sites with animal carbon isotope data by white circles; b) Map of the studied region, with white circles indicating the sites in Haryana analysed as part of this study, where the size of the circle relates to the site size in hectares (see legend).

Cattle and buffalo are the most abundant faunal species identified in Indus contexts, with their bones often comprising over 50% of the total sample (Joglekar et al., 2013; Miller, 2004; Thomas, 2002). Distinguishing between cattle and water buffalo remains is difficult, but studies indicate that cattle tend to outnumber buffalo (e.g. Harappa, Punjab: Miller, 2004; Dholavira, Gujarat: Patel, 2015), although the precise importance of cattle and water buffalo bones can vary between even relatively closely located settlements (e.g. Shikarpur and Bagasra, Gujarat: Chase, 2010, 2014). Cattle and water buffalo have markedly different water requirements, and it might be expected that proportions of water buffalo will have been exploited in areas with better water availability, though water buffalo have been attested in arid areas, such as at Dabli-vas Chugta in northern Rajasthan (Joglekar pers. comm.). Kill-off patterns tend to suggest that both species were kept primarily for their secondary products (Chase, 2010, 2014; Miller, 2004; Patel, 2015), although at Balakot, the kill-off pattern indicates that meat production was important (Meadow, 1979).

Sheep and goat bones typically make up *c.*10% of the animal remains at Indus settlements (Thomas, 2002), but their widespread presence indicates that they were a fundamental part of the economic system. Studies suggest that the proportion of sheep and goat varied, likely related to the environmental conditions at the site mediated by their cultural importance (Meadow, 1991; Miller, 2004; Patel, 1997). Kill-off patterns indicate some differences in the primary aim of sheep and goat pastoralism between sites, with the animals kept primarily for meat at the small coastal settlements at Shikarpur and Bagasra (Chase, 2010, 2014), while secondary products seem to have been more important at Dholavira, Harappa and Nausharo (Meadow, 1991; Patel, 2015), which are situated in island, alluvial plain and piedmont contexts respectively.

Pigs are often found in Indus settlements, but they typically represent only 2–3% of the zooarchaeological assemblage (Joglekar et al., 2013; Thomas, 2002). The domestic status of these animals remains unclear (Chase, 2014), but it is possible that both wild and domestic pig were exploited (Deshpande-Mukherjee et al., 2007; Joglekar et al., 2016).

Variation in animal resource use can be seen within several settlements, for example, differences can be seen in species and element representation, as well as cutmark abundance between intra- and extramural assemblages at Shikarpur and Bagasra (Chase, 2010, 2012, 2014). There are also hints at developments in the animal economy through time, with changes in cattle slaughter ages suggesting an increase in the importance of secondary products at Balakot and Harappa, and potentially at the regional or civilisation level (Meadow, 1979; Miller, 2004). It is likely that this intensification of pastoral production, whether local or regional, was linked to the increased subsistence needs of an increasing urban population (Miller, 2004).

2.3. Carbon isotope analysis as an indicator of diet

Carbon isotope analysis of tooth enamel allows for an assessment of diet during the time of tooth formation. Here, carbon isotopes are used to distinguish between animal consumption patterns of two different types of plants, C_3 and C_4, which use different photosynthetic pathways (Vogel and Van der Merwe, 1977). Most plants use the C_3 photosynthetic pathway, including economically important plants such as wheat, barley and rice. Those species which follow the C_4 pathway are mainly clustered within a restricted number of families largely comprising herbaceous genera, including the Graminae (grasses). Browsable leafy perennials are uncommon in those families, and are typically C_3. Both natural grasslands and crop stands may in certain cases be dominated by C4 plants; C4 grasses may be abundant in tropical, arid and coastal ecosystems, while C4 crops include, maize, the millets, sorghum and sugar cane (Ehleringer and Monson, 1993). A literature review of plants in Haryana suggests that a small but notable proportion of edible plants in the region are C_4 (today, a very rough estimate of 13% of species edible to humans and/or animals use the C_4 pathway, although note that this is by species not by biomass: Lightfoot et al., 2018). Free-roaming animals in arid environments globally have been observed to consume diets based on both C_3 and C_4 plants, with proportions varying throughout the year (Balasse et al., 2002; Cadwallader et al., 2012; Feranec et al., 2009; Makarewicz and Pederzani, 2017).

The carbon isotope values in plants are incorporated into tooth enamel at the time of tooth formation and not subsequently altered (Balasse, 2002). While enamel formation is complex, in hypsodont teeth (found in caprines and bovids, but not pigs and humans) enamel forms in such a way that a chronological sequence is represented down the length of the crown (Balasse, 2002, 2003). The period represented by a tooth varies depending upon the tooth analysed and the species in question; cattle and caprine M2s and M3s represent approximately the second and third year of life, respectively (Brown et al., 1960; Weinreb and Sharav, 1964). In animals eating a pure C_3 diet, variation in sequential enamel carbon isotope values can often be seen throughout the year due to seasonal variation in plant isotope values (Balasse, 2002, 2003; Heaton, 1999; O'Leary, 1988). In the mixed C_3-C_4 context of northwest India, however, we predict that any variations based on seasonal changes in plant isotope values will be swamped by variations in the proportion of C_3 and C_4 plants in the diet as this has the potential to induce much larger amounts of isotopic variation (Balasse, 2003; Chakraborty et al., 2018; Chase et al., 2014; Chase et al., 2020).

3. Materials and methods

Samples were selected from seven small settlement sites excavated by the *Land, Water and Settlement* and *TwoRains* projects (Petrie et al., 2017, 2019, 2020), and from a nearby settlement of Farmana, excavated by the Deccan College-RIHN Indus Project (Shinde et al., 2011). The Indus Civilisation phases of occupation at these sites provide the majority of our samples, though some individuals were sampled from later Painted Grey Ware and Early Historic period deposits for comparison. The sites range in size from 1 to 18 ha, and are situated in areas where modern rainfall amounts vary from 330 to 790 mm/annum. In addition, a small number of samples were taken from Ganeshwar, which is a Ganeshwar-Jodhpura Cultural Complex site located in Rajasthan that is broadly contemporary with the Early and Mature Harappan phases in Haryana (Singh et al., 2019; also Rizvi, 2007, 2013). The analysed sites are described in Appendix 1, summarised in Table 1 and shown in Fig. 1. Today, the sites are situated in semi-arid environments that have been completely transformed through modern farming. As best as we can currently ascertain, during the Indus period the sites would have been situated in relatively open grassland with various arid and riparian taxa (Üstünkaya et al., 2020).

At many of these sites, the availability of suitable faunal material has been severely limited by the preservation conditions. The teeth sampled were therefore often not the optimum samples for this type of analysis, but second and third molars were prioritised where possible. Domesticated animal teeth were collected from all sites, with wild animal teeth sampled wherever suitable teeth where available. In the case of hypsodont teeth (i.e. sheep, goat, cow and water buffalo, plus most of the wild species sampled here), sequential samples were taken where preservation permitted, with bulk enamel samples taken for the remaining teeth. Enamel powder samples were taken using a hand-held drill with a diamond drill bit attachment. For sequential samples, enamel subsamples were taken at perpendicular increments along a single cusp of the tooth, while bulk samples were taken along the length of the surviving crown. The pre-treatment method was based on that described in Balasse et al. (2002). 0.1 ml of 2–3% aqueous sodium hypochlorite was added per mg of sample. The samples were then left for 24 h at 4 °C before being rinsed five times with distilled water to remove the sodium hypochlorite. After this 0.1 mg of acetic acid was added per mg of sample. The samples were then left for 4 h at room temperature, before the acetic acid was removed and the samples were

Table 1
Information about sites and samples studied for this work.

Site name	Site code	Lat	Long	Phasing of samples	Size of site (ha)	Modern rainfall (mm/yr)	Koppen-Geigger climate classification	Number of samples
Alamgirpur	ALM	29.00	77.37	MHar iii, PGW, Mediaeval/PGW, Early Historic	1	790	Cwa: humid subtropical climate	21 individuals
Burj	BRJ	29.66	75.64	MHar i, PGW, Early Historic	1	450	BSh: semi-arid climate	7 individuals
Dabli-vas-Chugta	DVC	29.53	74.17	Mhar i, Mhar ii, Early Historic	6	330	BWh: desert climate	13 individuals
Farmana	FRM	29.04	76.31	MHar ii	18	510	BSh: semi-arid climate	16 individuals
Ganeshwar	GWR	27.67	75.82	GWR-JOD	3	470	BSh: semi-arid climate	5 individuals
Khanak	KNK	28.91	75.87	EHar	1	440	BSh: semi-arid climate	4 individuals
Lohari Ragho	LHR	29.25	76.03	MHar ii	9	510	BSh: semi-arid climate	11 individuals
Masudpur I	MSDI	29.24	75.97	MHar ii, MHar iii	6	440	BSh: semi-arid climate	23 individuals
Masudpur VII	MSDVII	29.21	75.95	MHar iii, ELHar	1	440	BSh: semi-arid climate	14 individuals

Rainfall data from the NASA Langley Research Center [LaRC] POWER Project funded through the NASA Earth Science/Applied Science Program.

rinsed. Samples were then frozen and freeze-dried to remove any remaining liquid.

The samples were then transferred to a vial with a screw cap holding a septa and PCTFE washer to make a vacuum seal, and reacted with 100% orthophosphoric acid at 90 °C using a Micromass Multicarb Sample Preparation System. The carbon dioxide produced was dried and transferred cryogenically into a VG SIRA mass spectrometer for isotopic analysis. Carbon isotopic ratios are expressed as δ values on the international VPDB scale calibrated using the NBS19 standard (Coplen 1995; Craig 1957). Each run of samples was accompanied by 10 reference carbonates (Carrara Z) and 2 control samples (Fletton Clay). Carrara Z has been calibrated to VPDB using the international standard NBS19, and the precision is better than ± 0.08‰.

Statistical analyses were performed using Rstudio version 1.0.143 (R Core Team, 2017). The code is available in Appendix 2, and the data file in Appendix 3. Samples were tested for normality using histograms and Shapiro-Wilks tests and for equality of variance using Levene's tests. Kolmogorov Smirnov Z tests were used for non-parametric data. Graphs were plotted using ggplot2 (Wickham, 2016).

4. Results

4.1. Comparisons across all individuals

We compared the data across all individuals. Where the enamel sample was taken as a bulk sample, we have used the single measured value. Where the enamel was sampled sequentially from one tooth, we have used the median value. Where two teeth were analysed sequentially from one individual, we used the median value of both teeth combined.

Bovids had higher carbon isotopic values than ovicaprids (cow and water buffalo versus sheep and goat: two-sampled Kolmogorov-Smirnov Z test, D = 0.89899, $p < .001$, Mature Harappan period only), and the few pigs and boar had values towards the bottom of the isotopic range for all domestic animals (Fig. 2, Table 2). Although sample size is limited we note that sheep and goat have similar carbon isotope ratios despite sheep being primarily grazers and goats primarily browsers. The wild animals (all of which are ruminant) show a wide range of $\delta^{13}C$ values. There is no apparent correlation between whether a species is classified as a browser or a grazer and its carbon isotope ratio. For example, blackbuck is classified as a grazer and yet has both low and high measured $\delta^{13}C$ values, while some four-horned antelope samples have very high carbon isotope ratios despite being classified as a browser.

4.2. Intra-individual variation

The $\delta^{13}C$ results of the sequential samples are summarised by tooth in Table 3 and listed in full in Appendix 4. Collectively, the wild animals show an extremely wide range of values, spanning from −8.6 to 4.3‰ (n = 15 teeth, n = 80 sub-samples, excluding *Sus scrofa*) (Fig. 3). The range found in individual teeth is generally large (ten have ranges over 1‰) although there are some notable exceptions, such as KNK01 (*Axis axis,* 9 samples, range = 1.0‰). Within the wild animal species sampled, different individuals follow different browsing and grazing patterns over time, as visible in the varied intra-individual ranges observed, notably for blackbuck (*Antilope cervicapra*) and four-horned antelope (*Tetracerus quadricornus*).

In the domestic species, the cattle and water buffalo results show similar patterns to each other over time and site (Figs. 4 and 5 by time, Fig. 6 by site), with each individual showing little isotopic change along the length of the tooth – the mean range for both cattle (n = 56 teeth, n = 509 subsamples) and water buffalo (n = 11 teeth, n = 83 subsamples) is 1.1‰. The sheep and goat show a different pattern to the bovids, although the sample size is considerably smaller (n = 15 teeth, n = 95 subsamples). In the urban phase (Mature Harappan), the sheep and goat show higher variation within a tooth than the cattle and water buffalo, tested using both the intra-individual range and also the variance across those ranges (mean intra-individual range in ovicaprids = 3.8‰, n = 11, mean intra-individual range in bovids = 1.1‰, n = 43, two-sampled Kolmogorov-Smirnov Z test, D = 0.77167, $p < .001$; Levene's test on variation of intra-individual ranges, df = 1, 52, F = 27.262, $p < .001$), although we note that the sample sizes are unequal. For samples that post-date the urban phase, the isotopic patterning varies. The single Late Harappan goat shows high isotopic variation (MSD_191, mean = −1.3‰, range = 4.7‰). The three post-Indus sheep and goat samples show less intra-individual variation and have higher $\delta^{13}C$ values than the earlier dated sheep and goat teeth (Fig. 4).

The cattle and water buffalo teeth from Ganeshwar, which is a contemporary but non-Indus site, also follow the pattern seen for these species at the other sites, having relatively high $\delta^{13}C$ values with little isotopic variation within each tooth (minimum $\delta^{13}C$ value = −1.5‰, maximum range = 1.6‰, n = 4 teeth).

There are some exceptions to the patterns of consistent and high bovid $\delta^{13}C$ and variable ovcaprid $\delta^{13}C$ over time. For instance, a few cattle and water buffalo have lower values than others (e.g. during MHar ii and MHar iii from both Masudpur I and Alamgirpur: Figs. 5 and 6), but even these samples have generally high $\delta^{13}C$ values and relatively low ranges of values within each tooth. There are also some sheep and goat with isotope values more akin to the cattle, most notably sample ALM_135, which is the only urban period ovicaprid sampled from Alamgirpur.

5. Discussion

5.1. Animal management strategies across space and over time

Using the expected offsets between isotopic values of diet and tooth enamel (+14.6‰ for ruminants and + 13.3‰ for pigs), our data

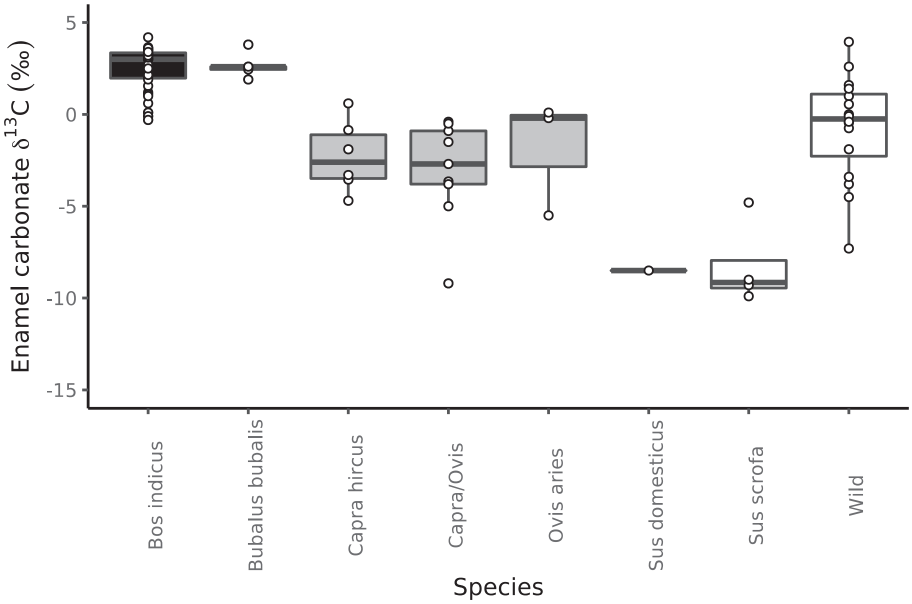

Fig. 2. Boxplot of enamel carbonate carbon isotope results summarised by individual from Mature Harappan period domestic animal species, with all wild animals shown for comparison.

Table 2
Summary of tooth enamel carbon isotope data from the Mature Harappan period by species.

Species	n	$\delta^{13}C$ (‰)					
		Mean	Standard deviation	IQR	Minimum	Maximum	Range
Bos indicus	39	2.5	1.2	1.4	−0.3	4.2	4.6
Bubalus bubalis	5	2.7	0.7	0.2	1.9	3.8	1.9
Capra hircus	6	−2.3	2.0	2.4	−4.7	0.6	5.3
Capra/Ovis	9	−3.1	2.8	2.9	−9.2	−0.4	8.7
Ovis aries	3	−1.9	3.2	2.8	−5.5	0.1	5.6
Sus domesticus	1	−8.5	NA	NA	NA	NA	NA
Sus scrofa	4	−8.3	2.3	1.5	−9.9	−4.8	5.0

indicate domestic and wild animal dietary intakes range from predominantly C_3 to predominantly C_4 (Passey et al., 2005). Some of the wild animals show marked seasonal variation in the relative proportions of C_3 and C_4 in their diets, while others vary little throughout the time represented by the samples. These data support the assertion that the landscape contained a mixture of C_3 and C_4 plants, and indicate that specialised consumption of C_4 species was a plausible strategy for some but not all individuals. No individuals consumed a diet that was solely or largely reliant upon C_3 plants. Notably, wild animal diets do not show a division between browsers and grazers with a wide range of values seen within both predominantly browsing species (i.e. *Tetracerus quadricornus*) and predominantly grazing species (i.e. *Antilope cervicapra*).

The carbon stable isotope results show that the cows and water buffalo consumed diets that were extremely high in C_4 foodstuffs (dietary input of −12.1‰ for Mature Harappan cattle, for example). These diets were consistent both through the time of tooth formation and across the chronological periods represented by the samples analysed here (i.e. Early Harappan through to Mediaeval). The diets were also consistent across the environmental zones and the different sizes of settlements represented by these samples. The tooth enamel of three cattle and one water buffalo from Ganeshwar, which is not an Indus Civilisation site, also show this pattern, as do cattle and water buffalo analysed from Bagasra, Shikarpur and Jaidak in Gujarat (Chase et al., 2014; Chase et al., 2020). The published data from the contemporary Sorath culture site Kotada Bhadli, Gujarat have slightly lower, and possibly more varied, carbon isotope values, but are still indicative of a diet that was largely reliant upon C_4 plants year-round (Chakraborty et al., 2018). The consistency and dominance of C_4 plants in cattle and water buffalo diets, combined with the expectation that the landscape contained a mixture of C_3 and C_4 species (Shoko et al., 2016; Lightfoot et al., 2018) and the range of diets apparent in the wild animal dataset regardless of whether the species are browsers or grazers, suggests that the diets of cattle and water buffalo were constrained and controlled by humans throughout the year. If these animals ate freely one would expect to see more variation in the cow and water buffalo diets. Human control of these animal diets could include giving the cows and water buffalo access to millet fields after harvest, as well as more direct foddering of wild and/or domesticated C_4 plant species to these animals.

During the Indus urban period (i.e. Mature Harappan), the sheep and goats show a range of carbon isotope values within a tooth indicating a more varied diet (in terms of the ratio of C_3 to C_4 plants) throughout the time of tooth formation. The sample size is much more limited than for cattle and water buffalo, due to the lower numbers of sheep and goat found on Indus sites, combined with the poorer preservation of sheep and goat teeth compared to larger cow and water buffalo teeth. Nevertheless, there does not seem to be a difference in diet between sheep and goats based on their preference for browse or graze. Furthermore, the dietary pattern for sheep and goat seems to be consistent across the Indus sites analysed here, and is similar to the pattern found at Bagasra, Shikarpur, Jaidak and Kotada Bhadli, although at this latter site there is one sheep with carbon isotope values indicative of a C_4 dominated diet (Chakraborty et al., 2018; Chase et al., 2014; Chase et al., 2020). The single Late Harappan individual also seems to follow this pattern, as do the Late Harappan individuals from Jaidak. The data suggest that the sheep and goat generally consumed a seasonally varied diet, which at times was dominated by C_4 plants and at other times contained a high proportion of C_3 plants. The lack of dietary consistency both within and between individuals suggest that humans exerted far less control over the diets of sheep and goat than over cow and water buffalo, although direct foddering of sheep and goat using C_3 and/or C_4 plants at various times of the year remains possible. This similarity in diet between sheep and goat is somewhat surprising given their well-known preferences for graze and browse,

Table 3
Enamel carbonate carbon isotope data from bulk and sequential intra-tooth samples summarised by individual.

Specimen	Tooth	Species	Site	Period	n	$\delta^{13}C$ (‰)				
						Minimum	Maximum	Mean	Median	Range
ALM_031	M1/M2	*Sus scrofa*	ALM	MHar	1	−9.3	−9.3	−9.3	−9.3	0.0
ALM_033	M2	*Bos indicus*	ALM	MHar	6	1.9	2.9	2.2	2.1	1.0
ALM_034	M2	*Bos indicus*	ALM	MHar	5	−0.6	2.6	1.1	1.2	3.2
ALM_035	M2	*Boselaphus tragocamelus*	ALM	MHar	5	0.6	2.9	1.7	1.6	2.3
ALM_036	M3	*Bos indicus*	ALM	MHar	8	2.8	3.8	3.4	3.5	1.0
ALM_088	m3	*Antilope cervicapra*	ALM	MHar	2	−2.6	1.7	−0.5	−0.5	4.3
ALM_102	M1	*Sus domesticus*	ALM	PGW	1	−11.9	−11.9	−11.9	−11.9	0.0
ALM_114	M1	*Sus domesticus*	ALM	PGW	1	−11.6	−11.6	−11.6	−11.6	0.0
ALM_126	M2	*Sus scrofa*	ALM	MHar	1	−9.9	−9.9	−9.9	−9.9	0.0
ALM_128	M3	*Bos gaurus*	ALM	MHar	5	−1.4	1.3	−0.1	0.0	2.7
ALM_135	m3	*Ovis aries*	ALM	MHar	7	−2.1	1.2	−0.5	−0.2	3.3
ALM_152	M2	*Bos indicus*	ALM	MHar	10	0.7	2.3	1.5	1.6	1.6
ALM_153	M3	*Bos indicus*	ALM	MHar	9	−0.6	1.5	0.2	0.1	2.1
ALM_183	M3	*Bos indicus*	ALM	PGW	8	3.6	4.2	3.8	3.8	0.6
ALM_196	M2	*Tetracerus quadricornus*	ALM	PGW	7	0.1	4.1	1.6	1.0	4.0
ALM_200	M1/M2	*Capra hircus*	ALM	Medieval/PGW	1	−1.8	−1.8	−1.8	−1.8	0.0
ALM_230	M1/M2	*Capra/Ovis*	ALM	Early Historic	10	−0.4	1.0	0.3	0.3	1.4
ALM_232	M1	*Capra hircus*	ALM	Early Historic	5	0.4	1.3	0.8	0.7	0.9
ALM_259	m3	*Antilope cervicapra*	ALM	PGW	6	−1.0	1.8	0.6	0.6	2.8
ALM_NN011	M3	*Bos indicus*	ALM	PGW	7	2.9	3.8	3.5	3.5	0.9
ALMNN_013	M1/M2	*Capra/Ovis*	ALM	PGW	8	0.5	2.6	1.7	1.9	2.1
BRJ_636	m2	*Tetracerus quadricornus*	BRJ	PGW	3	2.3	3.0	2.6	2.6	0.7
BRJ_648	m2	*Tetracerus quadricornus*	BRJ	PGW	3	−4.6	−4.1	−4.4	−4.5	0.5
BRJ_652	M1/M2	*Bos indicus*	BRJ	PGW	1	2.7	2.7	2.7	2.7	0.0
BRJ_655	M3	*Bos indicus*	BRJ	PGW	9	2.8	3.6	3.2	3.1	0.8
BRJ_686	m3	*Bos indicus*	BRJ	MHar	10	2.9	3.6	3.3	3.3	0.7
BRJ_808	M3	*Bos indicus*	BRJ	Early Historic	11	2.7	3.8	3.1	3.1	1.1
BRJ_NN01	M1/M2	*Bos indicus*	BRJ	PGW	1	1.5	1.5	1.5	1.5	0.0
DVC_018	M3	*Capra hircus*	DVC	MHar	1	−1.9	−1.9	−1.9	−1.9	0.0
DVC_107	m3	*Bos indicus*	DVC	MHar	9	2.5	3.4	3.1	3.3	0.9
DVC_130	M1	*Capra/Ovis*	DVC	MHar	1	−9.2	−9.2	−9.2	−9.2	0.0
DVC_222	M3	*Capra hircus*	DVC	MHar	2	−3.9	−3.2	−3.6	−3.6	0.7
DVC_225	M2	*Bos indicus*	DVC	MHar	5	3.0	4.0	3.5	3.5	1.0
DVC_279	M3	*Bubalus bubalis*	DVC	Early Historic	9	3.2	3.7	3.6	3.6	0.5
DVC_502	M2	*Bubalus bubalis*	DVC	MHar	5	1.3	3.2	2.3	2.6	1.9
DVC_509	m2	*Bos indicus*	DVC	MHar	7	1.2	2.2	1.8	1.9	1.0
DVC_530	DP4	*Antilope cervicapra*	DVC	MHar	1	−7.3	−7.3	−7.3	−7.3	0.0
DVC_554	M2	*Sus scrofa*	DVC	MHar	1	−9.0	−9.0	−9.0	−9.0	0.0
DVC_558	M2	*Capra hircus*	DVC	MHar	2	−0.9	−0.8	−0.9	−0.9	0.1
DVC_560	M2	*Cervus unicolor*	DVC	MHar	6	−1.8	1.9	−0.4	−0.8	3.7
DVC_561	M1/M2	*Capra hircus*	DVC	MHar	4	−6.1	−2.4	−3.8	−3.3	3.7
FR_1704	M3	*Bos indicus*	FRM	MHar	11	0.4	1.9	0.9	0.6	1.5
FR_1706	M2	*Bos indicus*	FRM	MHar	11	2.0	3.7	3.0	3.0	1.7
FR_1709	M3	*Bos indicus*	FRM	MHar	14	2.1	3.2	2.7	2.7	1.1
FR_1711	M2	*Bos indicus*	FRM	MHar	5	2.3	2.7	2.5	2.6	0.4
FR_1711	M3	*Bos indicus*	FRM	MHar	8	2.9	3.1	3.0	3.0	0.2
FR_1713	M3	*Ovis aries*	FRM	MHar	12	−9.5	−3.2	−6.1	−5.5	6.3
FR_1716	M1/M2	*Capra/Ovis*	FRM	MHar	3	−3.2	−0.7	−1.6	−0.9	2.5
FR_1717	M1/M2	*Capra/Ovis*	FRM	MHar	9	−7.3	0.2	−4.0	−5.0	7.5
FR_1718	M3	*Bos indicus*	FRM	MHar	4	4.2	4.3	4.2	4.2	0.1
FR_1720	M3	*Bos indicus*	FRM	MHar	15	2.5	3.4	3.0	3.0	0.9
FR_1721	M3	*Bos indicus*	FRM	MHar	15	2.5	3.7	3.3	3.3	1.2
FR_1724	M3	*Bos indicus*	FRM	MHar	13	3.2	3.8	3.5	3.6	0.6
FR_1728	M1	*Capra/Ovis*	FRM	MHar	1	−0.4	−0.4	−0.4	−0.4	0.0
FR_1729	M3	*Bos indicus*	FRM	MHar	17	2.7	3.4	3.0	3.0	0.7
FR_1730	M3	*Bos indicus*	FRM	MHar	1	−0.3	−0.3	−0.3	−0.3	0.0
FR_1731	M3	*Bos indicus*	FRM	MHar	21	2.7	3.6	3.1	3.1	0.9
FR_1732	M3	*Antelope*	FRM	MHar	9	0.9	2.1	1.4	1.4	1.2
GWR032	M2	*Bos indicus*	GWR	GWR-JOD	4	−1.5	−0.6	−1.0	−1.0	0.9
GWR252	M2	*Bos indicus*	GWR	GWR-JOD	5	1.4	1.7	1.6	1.6	0.3
GWR548	M2	*Bubalus bubalis*	GWR	GWR-JOD	5	−1.0	−0.3	−0.6	−0.6	0.7
GWR554	M2	*Boselaphus tragocamelus*	GWR	GWR-JOD	5	−1.6	0.2	−0.5	−0.1	1.8
GWR75	M2	*Bos indicus*	GWR	GWR-JOD	6	0.3	1.9	0.9	0.8	1.6
KNK01	max molar	*Axis axis*	KNK	EHar	9	−0.9	0.1	−0.5	−0.4	1.0
KNK02	mandible	*Bos indicus*	KNK	EHar	12	0.8	2.2	1.4	1.5	1.4
KNK03	mandible	*Bos indicus*	KNK	EHar	13	3.3	4.3	3.8	3.8	1.0
KNK04	maxilla	*Bos indicus*	KNK	EHar	9	2.9	4.2	3.5	3.4	1.3
LHR02	LRM2	*Bos indicus*	LHR	MHar	6	2.1	2.8	2.6	2.7	0.7
LHR02	LRM3	*Bos indicus*	LHR	MHar	10	1.7	3.2	2.3	2.3	1.5
LHR03	LLM2	*Bos indicus*	LHR	MHar	15	2.2	2.9	2.5	2.4	0.7
LHR05	LRM2	*Bos indicus*	LHR	MHar	13	3.0	3.7	3.4	3.5	0.7
LHR05	LRM3	*Bos indicus*	LHR	MHar	13	3.4	4.2	3.9	3.9	0.8

(*continued on next page*)

Table 3 (*continued*)

Specimen	Tooth	Species	Site	Period	n	$\delta^{13}C$ (‰)				
						Minimum	Maximum	Mean	Median	Range
LHR07	ULM3	*Bos indicus*	LHR	MHar	11	2.4	3.2	2.7	2.7	0.8
LHR08	LLM2	*Bos indicus*	LHR	MHar	14	1.7	3.1	2.2	2.2	1.4
LHR09	LLM3	*Bos indicus*	LHR	MHar	12	2.1	2.6	2.4	2.5	0.5
LHR11	URM2	*Capra/Ovis*	LHR	MHar	1	−3.8	−3.8	−3.8	−3.8	0.0
LHR11	URM3	*Capra/Ovis*	LHR	MHar	1	−2.7	−2.7	−2.7	−2.7	0.0
LHR12	ULM2	*Bubalus bubalis*	LHR	MHar	5	1.0	2.1	1.6	1.6	1.1
LHR12	ULM3	*Bubalus bubalis*	LHR	MHar	9	1.5	2.5	1.9	1.9	1.0
LHR13	URM2	*Bos indicus*	LHR	MHar	13	3.0	3.5	3.3	3.3	0.5
LHR14	LRM3	*Bos indicus*	LHR	MHar	13	2.8	3.7	3.2	3.1	0.9
LHR15	LRM2	*Bubalus bubalis*	LHR	MHar	5	3.0	4.0	3.5	3.6	1.0
LHR15	LRM3	*Bubalus bubalis*	LHR	MHar	9	1.9	2.9	2.3	2.2	1.0
MSD_01	M3	*Capra/Ovis*	MSDI	MHar	1	−0.5	−0.5	−0.5	−0.5	0.0
MSD_02	M3	*Capra/Ovis*	MSDI	MHar	12	−6.9	−0.4	−3.3	−3.7	6.5
MSD_023	M2	*Ovis aries*	MSDI	MHar	2	−1.5	1.7	0.1	0.1	3.2
MSD_025	M1/M2	*Bos indicus*	MSDI	MHar	1	1.0	1.0	1.0	1.0	0.0
MSD_026	M1/M2	*Bos indicus*	MSDI	MHar	1	3.5	3.5	3.5	3.5	0.0
MSD_03	M2	*Bos indicus*	MSDI	MHar	10	−1.2	2.2	0.2	0.1	3.4
MSD_031	M1	*Sus scrofa*	MSDI	MHar	1	−4.8	−4.8	−4.8	−4.8	0.0
MSD_04	M2	*Bubalus bubalis*	MSDI	MHar	10	1.6	3.2	2.6	2.6	1.6
MSD_044	m3	*Capra hircus*	MSDI	MHar	5	−6.3	−0.8	−4.0	−4.7	5.5
MSD_05	M2	*Bos indicus*	MSDI	MHar	10	−0.2	1.6	1.0	1.1	1.8
MSD_063	M2	*Capra/Ovis*	MSDI	MHar	1	−1.5	−1.5	−1.5	−1.5	0.0
MSD_076	m3	*Bubalus bubalis*	MSDI	MHar	3	3.7	4.0	3.8	3.8	0.3
MSD_077	m2	*Boselaphus tragocamelus*	MSDI	MHar	4	3.3	4.3	3.9	4.0	1.0
MSD_089	M1/M2	*Bos indicus*	MSDI	MHar	1	3.5	3.5	3.5	3.5	0.0
MSD_092	M2	*Bos indicus*	MSDI	MHar	6	2.4	3.9	3.2	3.2	1.5
MSD_101	M2	*Antilope cervicapra*	MSDI	MHar	4	−8.6	−3.8	−6.7	−7.2	4.8
MSD_101	M3	*Antilope cervicapra*	MSDI	MHar	5	−4.6	−1.5	−2.8	−3.0	3.1
MSD_125	M1	*Sus domesticus*	MSDI	MHar	1	−8.5	−8.5	−8.5	−8.5	0.0
MSD_139	M2	*Bos indicus*	MSDI	MHar	7	3.1	3.5	3.3	3.2	0.4
MSD_15	M1	*Capra hircus*	MSDVII	MHar	9	−0.9	1.7	0.4	0.6	2.6
MSD_155	M1/M2	*Bos indicus*	MSDI	MHar	1	3.6	3.6	3.6	3.6	0.0
MSD_156	M2	*Bos indicus*	MSDI	MHar	1	3.4	3.4	3.4	3.4	0.0
MSD_175	M2	*Bubalus bubalis*	MSDVII	LHar	12	1.2	3.3	2.6	2.8	2.1
MSD_176	M1/M2	*Antilope cervicapra*	MSDVII	LHar	1	−3.4	−3.4	−3.4	−3.4	0.0
MSD_177	M2	*Bubalus bubalis*	MSDVII	LHar	11	3.5	4.4	3.9	3.7	0.9
MSD_191	M2	*Capra hircus*	MSDVII	LHar	5	−4.2	0.5	−1.3	−1.2	4.7
MSD_5115	M2	*Bos indicus*	MSDVII	LHar	2	3.3	3.5	3.4	3.4	0.2
MSD_5115	M3	*Bos indicus*	MSDVII	LHar	4	2.2	2.4	2.3	2.3	0.2
MSD_5117	M3	*Bos indicus*	MSDVII	LHar	2	3.8	3.9	3.9	3.9	0.1
MSD_5118	M3	*Bos indicus*	MSDVII	LHar	10	3.7	4.6	4.0	4.0	0.9
MSD_5121	M2	*Bos indicus*	MSDVII	LHar	5	3.9	4.2	4.1	4.1	0.3
MSD_5125	m3	*Bos indicus*	MSDVII	LHar	4	−1.0	0.9	0.1	0.3	1.9
MSD_5126	M3	*Bos indicus*	MSDVII	LHar	6	3.6	4.0	3.7	3.6	0.4
MSD_5145	M3	*Sus scrofa*	MSDVII	LHar	1	−5.7	−5.7	−5.7	−5.7	0.0
MSD_5146a	M1/M2	*Bos indicus*	MSDVII	LHar	3	1.0	3.1	1.9	1.5	2.1
MSD_5146b	M2	*Bos indicus*	MSDVII	LHar	9	0.7	4.1	2.4	2.4	3.4
MSD_5153	M2	*Bos indicus*	MSDVII	LHar	5	3.2	3.6	3.4	3.5	0.4
MSD_NN010	M3	*Bos indicus*	MSDI	MHar	11	3.0	4.0	3.6	3.6	1.0
MSD_NN012	M3	*Antilope cervicapra*	MSDI	MHar	7	−3.4	−1.0	−2.2	−1.9	2.4
MSD_NN013	M2	*Bos indicus*	MSDI	MHar	8	−1.1	0.3	−0.2	−0.1	1.4

respectively. However both species can consume both graze and browse as part of their diets. It may well be that with further isotopic analyses of sheep and goat which have been identified to species (possibly via the use of ZooMS) differences between these two species will be seen based upon their dietary preferences (although we note that such distinctions were not visible in the wild animal species sampled either). Our data from later time periods suggest that this sheep and goat management strategy changed over time, as the small number of Painted Grey Ware and Early Historic samples have diets dominated by C_4 plants throughout the time of tooth formation, although with a sample size of three individuals, this conclusion must remain speculative. We also note that all three of these post-Indus samples are from Alamgirpur, and it may be that they represent a distinct local animal management tradition rather than a change through time. The single Mature Harappan sheep from Alamgirpur has carbon isotope values that are ambiguous in that they are relatively high but do show some variation.

The (bulk) carbon isotope values of pig/wild boar tooth enamel indicate a diet largely dependent upon C_3 resources. The individual identified as domestic has a carbon isotope value very similar to that of three of the four wild pigs, whilst one of the wild pigs has a mixed C_3-C_4 diet, similar to other wild ruminants we have analysed.

The archaeobotanical evidence suggests that many plant species were grown at Indus sites, including wheat, barley and rice (C_3), as well as (C_4) millets. The C_3 species were not being fed to cattle and buffalo in significant quantities at the analysed sites, although they may have been fed to sheep, goat and pig. While isotopic evidence from human remains is very scarce, data from Harappa (Kenoyer et al., 2013) suggest that human diets here were based upon C_3 resources. If these human data from Harappa are representative of other areas of the Indus, it is possible that large grained, C_3 cereals were reserved for human consumption while small grained cereals (i.e. millets) were grown for forage, and consumed by humans only as a famine food.

In summary, these data suggest at least two and potentially three

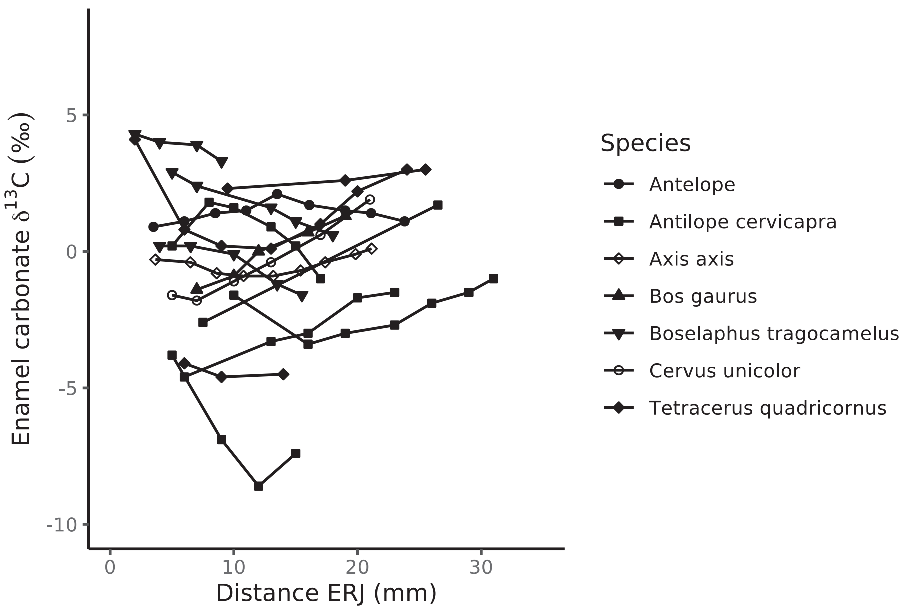

Fig. 3. Scatter plot showing enamel carbonate sequential intra-tooth carbon isotope results from wild animal species, plotted as a function of distance from the enamel root junction (ERJ).

different domestic animal diets during the Mature Harappan period: one for cattle and water buffalo who largely consumed C_4 plants; another for sheep and goat who ate both C_3 and C_4 plants but in varying proportions throughout the year; and, potentially, a third for pigs who consumed largely C_3 resources. The data from wild animals suggest that a free roaming animal could occupy a range of ecological niches, but generally the wild species' diets are most similar to those of the sheep and goat. It therefore seems reasonable to suggest that very different animal management strategies were practised for the three groups of domestic animals. In the case of the cows and water buffalo, whose access to food was possibly highly restricted by humans, it seems likely that these animals were kept close by, potentially within settlements,

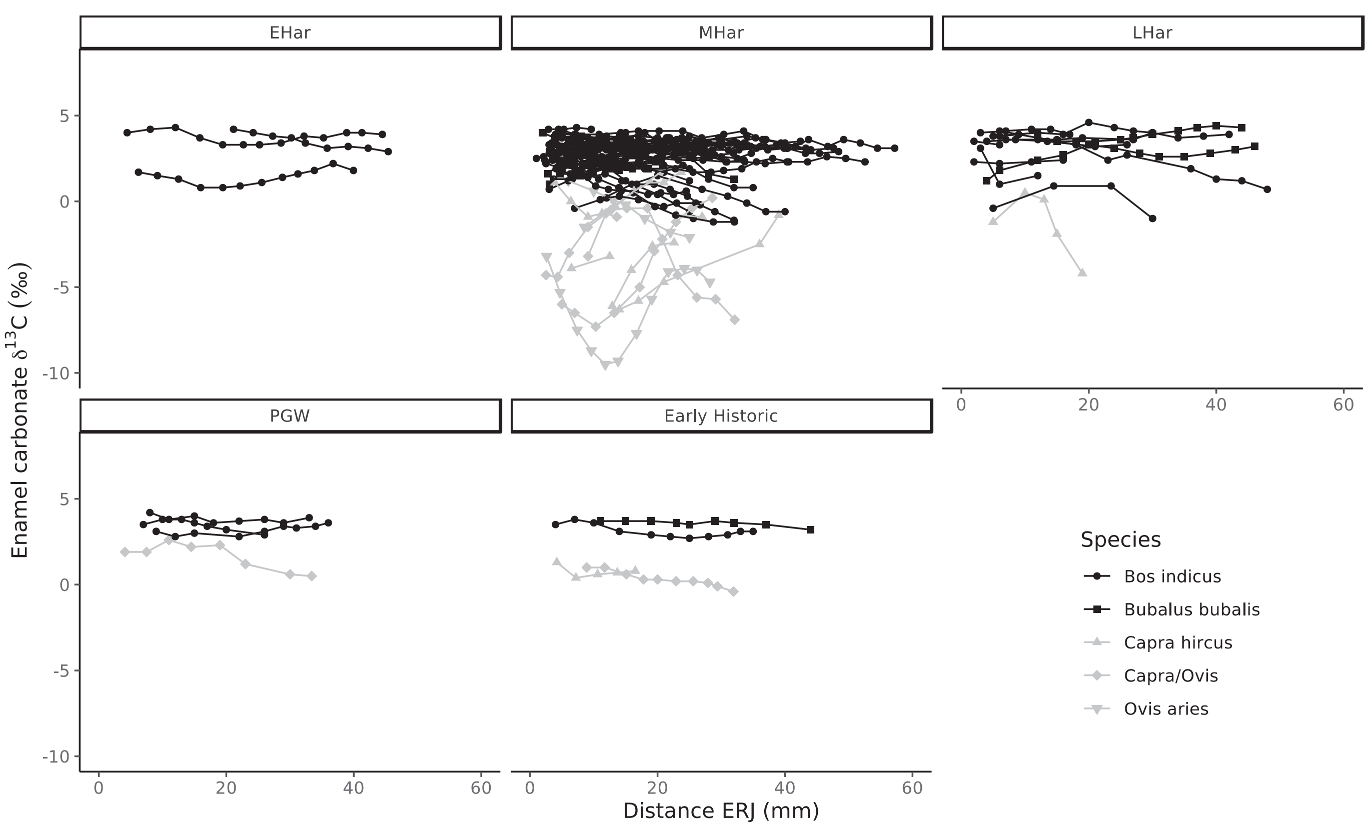

Fig. 4. Scatter plot showing enamel carbonate sequential intra-tooth carbon isotope results from domestic animal species, separated by chronological period, plotted as a function of distance from the enamel root junction (ERJ). The periods shown are Early Harappan (EHar), Mature Harappan (MHar), Late Harappan (LHar), Painted Grey Ware (PGW) and Early Historic.

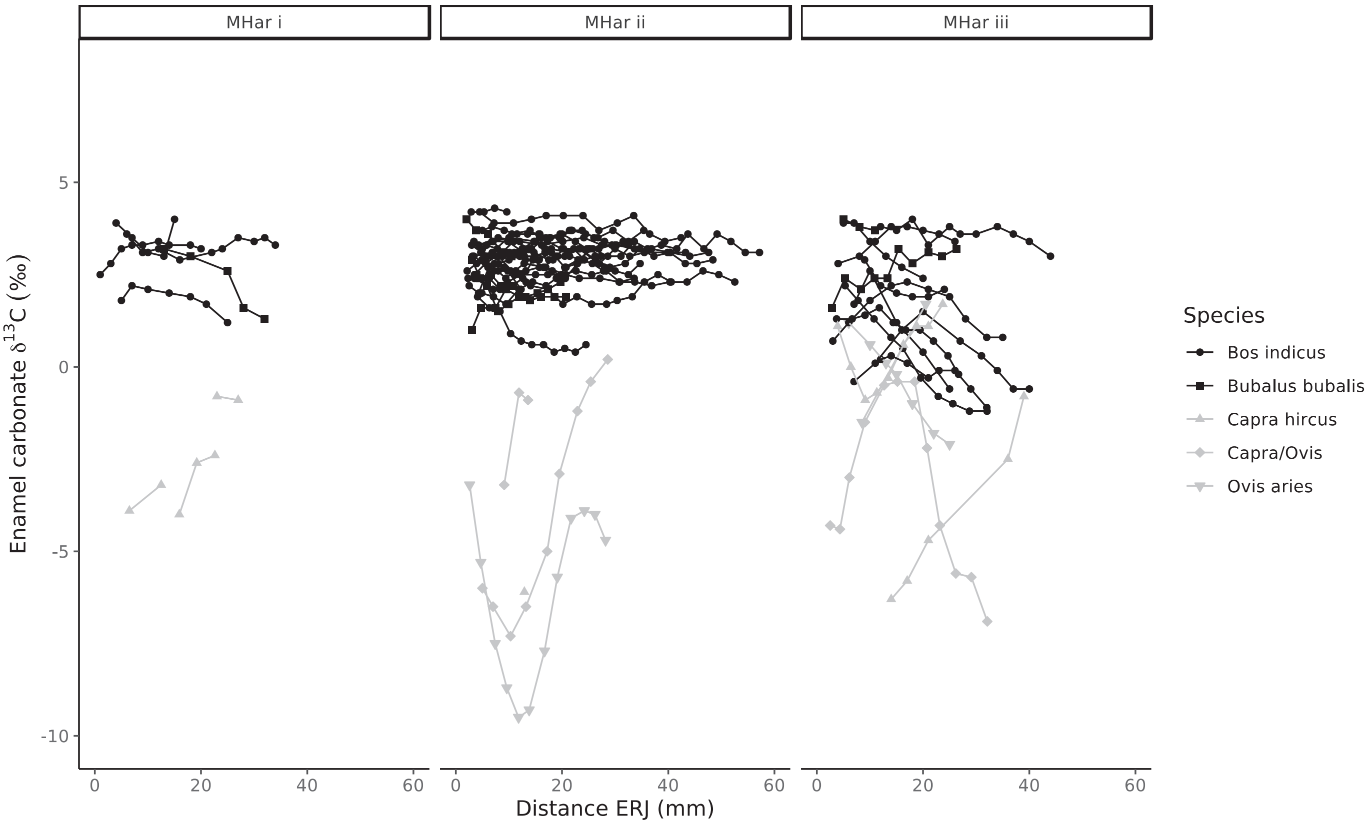

Fig. 5. Scatter plot showing enamel carbonate sequential intra-tooth carbon isotope results from Mature Harappan period domestic animal species, separated by chronological phase, plotted as a function of distance from the enamel root junction (ERJ).

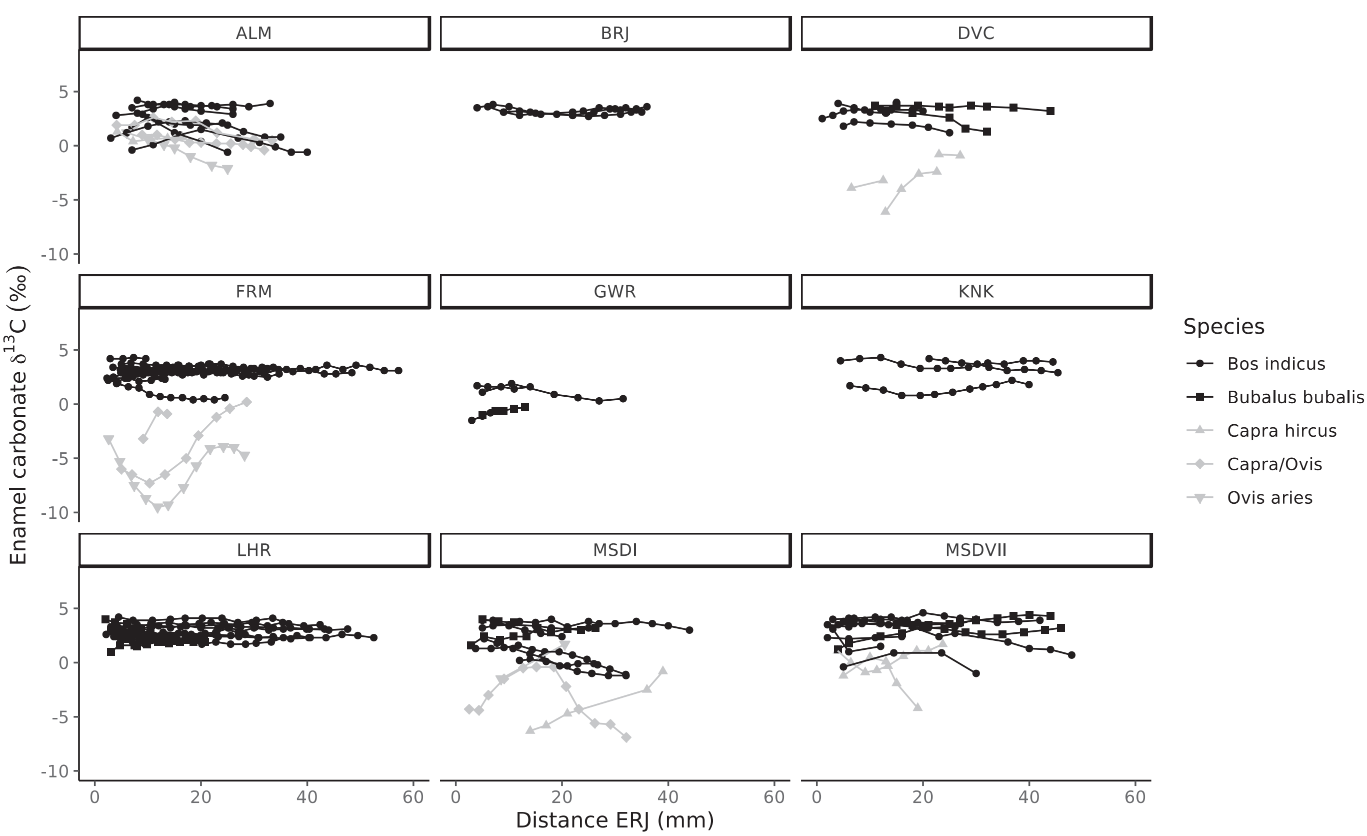

Fig. 6. Scatter plot showing enamel carbonate sequential intra-tooth carbon isotope results from domestic animal species, separated by site, plotted as a function of distance from the enamel root junction (ERJ). Site names and codes given in Table 1.

and their mobility was restricted on a day-to-day basis. This reconstruction fits well with the use of these animals for traction, ploughing, transport and dairying, but does not preclude the possibility of long-distance movement and trade of animals. A far more mobile and less constrained management strategy is likely for sheep and goats, which probably roamed more freely in the landscape for at least part of the year. Again, this day-to-day mobility strategy does not preclude the possibility of long-distance trade in animals, nor did this mobility strategy necessarily involve flocks travelling long distances.

Testing these animal management strategies through the direct analysis of animal movement using strontium isotope analysis is likely to be difficult if sheep and goat were not moved very far on a day to day basis. If this were the case, the strontium isotope ratios of sheep and goat may well reflect a local signal, bearing in mind that the 'local' signal reflects geology and therefore might equate to a large area of the countryside. When one considers that long-distance movement of animals is to be expected within the Indus context, whether for agricultural or transportation purposes (there was certainly long-distance trade of other, non-perishable, raw materials and commodities; Kenoyer, 1998; Law, 2011; Wright, 2010), then it is likely that any local mobility signal will be insignificant compared to the isotopic variation caused by long-distance movement.

5.2. Implications for separation of agricultural tasks during the Mature Harappan period

How would such an animal management strategy have worked in practice during the Mature Harappan period? The scenario outlined above involves, for at least part of the year, cattle and water buffalo (and perhaps pigs) being kept close to home while the sheep and goat roamed the landscape. In practical terms, it is unlikely that one person would have been able to manage both of these groups of animals, let alone be able to grow crops as well. These data thus suggest a scenario whereby there were at least two people, or potentially two groups of people, who performed different agricultural tasks related to animals at Indus settlements. Many different ways of dividing tasks between people can be imagined, including but not limited to: different people within a household (children versus adults, males versus females, or simply based on personal preference); different households within a settlement with different agricultural specialisms; agriculturally specialised settlements; and two entirely different social groups – more mobile pastoralists concentrating on sheep and goat and who could also have grown less labour intensive crops (such as some species of millet), and settled mixed agriculturalists focusing on cattle and arable agriculture.

There are several ways that these separation of task scenarios can and should be tested. For example, if there were two groups of people living mobile and sedentary lifestyles, one would expect to find temporary settlements alongside permanent settlements. There is some evidence for this in Gujarat and Cholistan (Mughal, 1997; Rissman and Chitalwala, 1990). In Cholistan temporary camp sites are far more prevalent in the Hakra (i.e. pre-urban) and Late Harappan (i.e. post-urban) periods than they were during the urban phase, though none of these sites has yet been excavated. If these two groups further differed in their agricultural strategies along the lines discussed above, one would expect that the sites occupied by pastoral populations would have more neonatal lamb and kid remains as opposed to neonatal calves, and vice versa for the permanent settlements. Further, in terms of arable production, while the mobile groups likely consumed grain, one would perhaps expect to find archaeobotanical evidence biased towards grain *consumption* at temporary settlements, and archaeobotanical evidence for grain *production* and *consumption* at permanent sites, although we note that pastoralists often grow less labour intensive crops. Further, if human remains were available for analysis, one might expect mobile pastoralists to have osteological and isotopic evidence for high protein diets and high habitual mobility relative to settled populations.

While a plausible scenario, the hypothesis that there could have been permanent settlements which specialised in different animals (regardless of any arable activities) can reasonably be discounted given the available zooarchaeological evidence. If this were the case, then one would expect the proportion of animal remains in Indus zooarchaeological assemblages to show more variation, that is one would expect some settlements to specialise in raising sheep and goats and therefore to have a very high proportion of sheep and goat remains. However, the available evidence indicates that cows and water buffalo dominate zooarchaeological assemblages across the Indus Civilisation. Nevertheless, a further examination of neonatal animal remains at Indus sites would be welcome to provide additional evidence for or against this conclusion.

Testing the hypothesis that different households within a permanent settlement raised different species of animals is likely to be difficult, and would rely on the archaeological visibility of the above criteria (i.e. zooarchaeological and archaeobotanical evidence) on a household level. The absence of evidence for different groups and for household specialisation, combined with positive zooarchaeological evidence for young sheep/goat and cattle/water buffalo would likely suggest division of labour on a household level, although determining which individuals performed which tasks would be extremely difficult and rely upon osteological (and potentially human isotopic) evidence.

5.3. Adaptability, sustainability and resilience

Regardless of how the various agricultural tasks were organised in practice, it seems that a Mature Harappan strategy that led to different animal diets was successful, in that the isotopic pattern holds across the sites analysed here, and those published from Gujarat. This intra- and inter-regional similarity suggests that this animal management strategy was adaptable to the range of environmental and social conditions represented by the sites presented here and published sites in Gujarat. This lack of variation is in direct contrast to the evidence from archaeobotany which suggests variation between regions in arable agricultural patterns (Petrie and Bates, 2017; Weber, 1999; Weber et al., 2010), as discussed above.

Considering the data diachronically, it is clear that the consumption of C_4 plants by cattle and water buffalo was consistent through time from the Early Harappan through to the Early Historic period, at least at the sites analysed here. The implication is that C_4 plants were readily available and/or easy to grow, easy to gather and/or harvest, and produced a large amount of plant matter that was not otherwise being used by humans. The long time-frame involved suggests that this strategy was sustainable for at least 2000 years. Furthermore, this strategy persisted across the development, floruit and decline of Indus urbanism and in spite of the climatic changes associated with the 4.2 ka BP event and the subsequent period of unpredictable climate (Petrie et al., 2017). The persistence of this strategy suggests that it was resilient to acute challenges and sustainable over the long term.

Notably, our limited evidence suggests that the diet of sheep and goats did change through time, shifting from a less to a more managed or restricted food provision. Unfortunately, this assessment is hampered by the small sample sizes, and the fact that the three post-Indus sheep and goat all come from one site. It is therefore difficult to distinguish between a different animal management strategy at Alamgirpur and change through time. Given the consistency between the data from other sites, however, we tentatively suggest that change through time is the most likely of the two options. If this is the case, then this pattern would suggest that the Mature Harappan sheep and goat management strategy was less sustainable or less resilient than that of the cattle and water buffalo. One can speculate therefore that shifting sheep and goat diets towards C_4 foods may have removed risks associated with declining rainfall, as C_4 plant species tend to require less water and are thus more sustainable than C_3 plants when water is limited. One can also imagine a potentially related scenario whereby C_3 plant foods became less available through time, perhaps due to changing climate or changing social or environmental circumstances leading to a decline in available arable land. In this scenario, sheep and goat may have been competing with humans for C_3 plant foods and/or farmland, and sheep and goat diets were deliberately shifted towards C_4 plants, either to ensure that people had better access to C_3 plant foods like wheat and rice or because C_4 plant foods became more abundant, which is suggested by the available archaeobotanical evidence from the same sites (Bates, 2016; Bates et al., 2017, 2018; Petrie and Bates, 2017). An alternative suggestion might be that, for some reason, the mobility patterns of sheep and goat was reduced and therefore more direct foddering was necessary. Ultimately, confirming that such a change took place, and understanding why it occurred, will require much more research, particularly on sites post-dating the Indus period.

6. Conclusions

This study has shown that the dietary evidence for the animal management strategies employed in nine settlements in the north of the Indus zone were (isotopically) very similar to those from two Indus period sites in Gujarat. In the Mature Harappan period, cattle and water buffalo consumed high proportions of C_4 plants throughout the year, sheep and goat ate a diet containing both C_3 and C_4 species in variable proportions, while pigs consumed a diet largely based on C_3 foodstuffs. This pattern is also consistent across sites in different parts of northwest India, suggesting that it was adaptable to a range of environmental conditions. The high consumption of C_4 foodstuffs by cows and water buffalos is also consistent through time, suggesting that it was sustainable as well as resilient to adversity, and there are hints that this diet was adopted for sheep and goat in later periods. The evidence for different animal diets during the Indus urban period has implications for the management of herds and the organisation of society. There appears to be a clear separation of tasks within individual settlements and communities, though further research is needed to understand if the implied separation of tasks was organised on a household, settlement or population level.

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Declaration of competing interest

The authors declare no competing interests.

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Author statement

EL, PJJ and CP conceptualised the study, EL carried out the formal analysis, EL, PJJ, MTD, ES, JM carried out the investigation, PPJ, VS, RNS and TCOC provided resources, MKJ and CAP engaged in funding acquisition, RNS, MKJ and CAP provided project administration, MKJ, TCOC and CAP provided supervision, EL and CAP wrote the original draft, and EL, PJJ, PPJ, MTD, ES, JM, RNS, MKJ, TCOC and CAP were involved with review and editing.

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